Transactions of the Royal Society of Edinburgh: Earth Sciences, **91**, 207–219, 2000

A sustained felsic magmatic system: the Hercynian granitic batholith of the Spanish Central System

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ABSTRACT: A batholith of around 10,000 km^2 was formed during the Hercynian orogeny in the Spanish Central System (SCS). Geochronological data indicate concentrated magmatic activity during the period 325–284 Ma. This late-orogenic magmatism is essentially granitic with only minor associated basic rocks (< 2% in outcrop). The SCS is a remarkably homogeneous batholith showing a restricted range of geochemical granite types without any evolutionary pattern related to time. These peraluminous granites show a limited variation in Na_2O/K_2O) (0·60–0·95), K/Rb (140–240), $(La/Yb)_n$ (6–13), and Eu/Eu* (0·34–0·62) ratios. This constancy in chemical characteristics is also reflected in their isotopic signatures: most monzogranites have initial $^{87}Sr/^{86}Sr$ ratios in the range of 0·7073–0·71229, initial εNd values vary between −5·4 and −6·6 and $\delta\ ^{18}O$ values group in the restricted range of 8·9–9·6‰. The lack of significant differences among SCS granitoids, maintained during a long geological period, suggests constancy in the nature of their source regions and conditions of magma generation. (1) *Limited range of crustal sources*: an essentially magmatic recycling during Hercynian orogen is suggested. Mantle-derived components are very limited and restricted to a minor role in the origin of the batholith. Geochemical and isotopic features of SCS granitoids are compatible with felsic lower crustal sources. (2) *Constraints in melt conditions*: uniformity in residual mineral assemblages (feldspars and garnet are always present in the granulitic residua) combined with a lack of attainment of equilibrium conditions during accessory phase dissolution in the crustal melting process is suggested. Granitic melts never reach saturation in some trace elements (REE, Th, Y, Zr), restricting their chemical variability. (3) *Homogenisation in magma chambers*: long-lived magmatic systems whose successive pulses accumulate into large magma chambers have the opportunity to mingle, thus reducing source differences.

KEY WORDS: collision granites, crustal anatexis, geochemistry, Hercynian Iberian Belt, isotopes, peraluminous batholith

A voluminous batholith of around 10,000 km^2 (~ 100,000 km^3) was built during the Hercynian orogeny in the innermost continental region of the Iberian Belt, the Spanish Central System (SCS). The batholith is made of more than 100 intrusive units, mainly monzogranite in modal composition, that were emplaced during a time span of around 40 Ma (Villaseca *et al.* 1995). Granitoids are the dominant rock in the SCS region, forming more than 85% of the outcropping surface in most parts. This batholith defines a clear geographical and geological unit separated by Precambrian and pre-Ordovician metamorphic series from western Hercynian granitic belts, not studied in this work. Nevertheless, the granitic belt of S Toledo, separated by Cenozoic sedimentary rocks of the Tagus basin, seems to be related to this central granitic block (Fig. 1).

The geochemical and petrological data set was collected during the last two decades by different authors in the three main sectors of the batholith: the eastern Sierra de Guadarrama (Brandebourger 1984; Casillas 1989; Pérez-Soba 1991; Villaseca *et al.* 1993; Villaseca *et al.* 1998a), the central Gredos Massif (Bea 1985; Moreno-Ventas *et al.* 1995; Herreros 1998) and the western Sierra de Béjar (Rottura *et al.* 1989; Recio *et al.* 1992; Pinarelli & Rottura 1995). With all these data, it is possible to envisage a remarkably homogeneous granitic batholith. Several models have been proposed to explain the origin of the SCS granites: (a) partial melting of essentially crustal sources (Villaseca *et al* 1998a; Bea *et al.* 1999); (b) hybridisation between crustal melts and mantle-derived magmas (Pinarelli & Rottura 1995; Moreno-Ventas *et al.* 1995); (c) crustal assimilation after hybridisation (Ugidos & Recio 1993).

The aim of this work is to emphasise the long-term magmatic geochemical patterns in the SCS batholith when compared with other granitic batholiths from different geodynamical settings: plate margins, intracontinental rifts or other collision-related granitoids. Melting of felsic lower crustal levels is proposed as the origin for this long-lived felsic and geochemically homogeneous magmatism.

1. The Hercynian plutonic event

The Hercynian orogeny is considered to have begun in this region just before the interruption of the Paleozoic sedimentation in lower to middle Devonian times (408–387 Ma., Gutiérrez Marco *et al.* 1990). This age is close to that given by some discordant U–Pb zircon data in SCS metamorphic rocks, which give lower concordia intercepts around 380–370 Ma (Wildberg *et al.* 1989). No more sedimentation occurred in the sector until the local deposition of upper Stephanian detrital rocks with associated volcanics (dated as 287 Ma volcanism, Hernando *et al.* 1980), related to distensive tectonic basins of the eastern SCS domains. This age range of *c.* 100–120 Ma encompasses most Hercynian radiometric magmatic, metamorphic and cooling ages of the SCS.

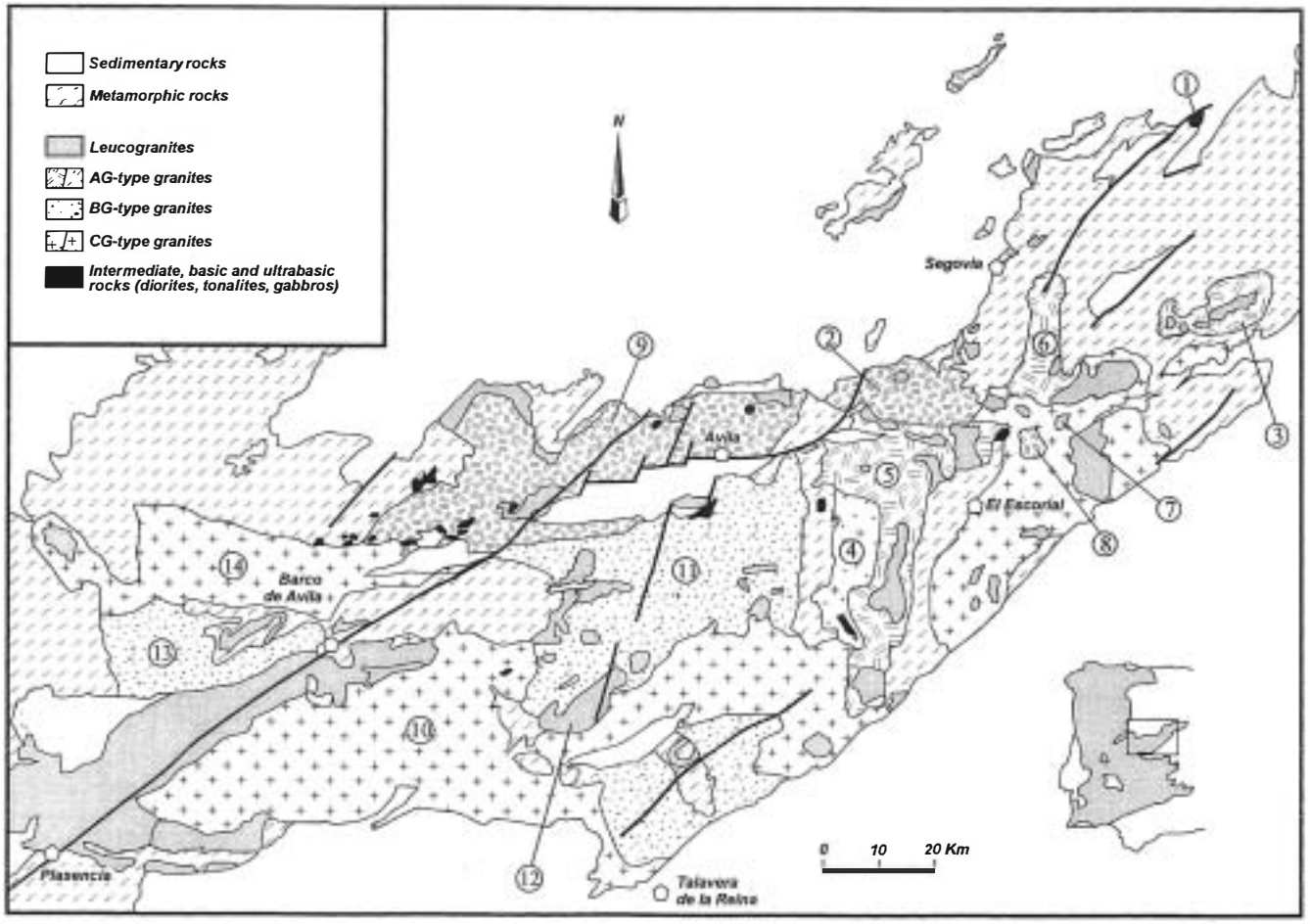

Figure 1 Geological sketch map of the Spanish Central System (SCS) and its location in the Hercynian Iberian Belt; granite-types in the legend are: AG-type = biotite granites with local accessory amphibole; BG-type = biotite granite *sensu stricto*; CG-type = biotite granites with accessory cordierite. Further explanation in section 2 of the text. Key to plutons: 1, Ventosilla; 2, Villacastin; 3, La Cabrera; 4, Hoyo de Pinares; 5, Navas del Marqués; 6, La Granja; 7, Cabeza Mediana; 8, Atalaya Real; 9, Cardeñosa-Avila; 10, Hoyos del Espino; 11, Navalosa; 12, Pedrobernardo; 13, Béjar BG; 14, Béjar CMG.

Hercynian tectonothermal evolution in the SCS is far from being well constrained. Nevertheless, most previous works describe a classical clock-wise P–T–t evolution of the Proterozoic and Palaeozoic rocks due to orogenic crustal thickening (Pereira 1992; Escuder Viruete *et al.* 1998). A first deep burial phase that reached eclogite/high-P granulite facies (Villaseca & Barbero 1994) was followed by a low-P/high-T event with widespread partial melting of the middle crust (resulting in migmatitic granulite-facies terranes such as those described by Pereira 1992; Barbero 1995; Martín Romera *et al.* 1999). Geochronology of this P–T evolution is poorly constrained; some concordant U–Pb monazite data in metasediments and felsic metaigneous rocks in the Guadarrama sector give ages in the range 337–326 Ma for the metamorphic peak in eastern Guadarrama (Escuder Viruete *et al.* 1998). Nevertheless, the metamorphic climax in the nearby Toledo granulitic areas is dated at *c.* 310 Ma (Barbero & Rogers 1999), suggesting a certain diachronism of the Hercynian metamorphic peak in central Spain.

Granitic plutonism mostly postdates the main tectonometamorphic events. This plutonism occurred *c.* 60 Ma after the beginning of the collision, but only 10 Ma after the mid-crustal emplacement levels reached metamorphic peak conditions. The granites are discordant with the surrounding rocks and produced contact aureoles. Plutonic magmatism is mainly concentrated in the range 323–284 Ma (Bea *et al.* 1994; Villaseca *et al.* 1995; Herreros 1998) although recent Rb–Sr geochronology in the easternmost pluton (Ventosilla) gives the oldest recorded age (343 Ma) for SCS intrusives (Villaseca *et al.* 1998b). Figure 2 shows the relationship of emplacement ages with the spatial distribution of major plutonic units in the eastern side of the batholith, where geochronological studies are more abundant. In this figure it is possible to discern that most of the batholith was built during the 323–303 Ma period with residual magmatic activity for another 20 Ma. This residual magmatism consists of small highly felsic plutons, usually less than 50 km^2 in surface area, and of coeval granitic porphyry dyke swarms (Fig. 2). Although available geochronological data (mainly based on Rb–Sr whole-rock isochrons) are still scarce (only 17 plutons are dated), the available results seem to be representative of the whole batholith as most of the dated plutons are major intrusive complexes (> 150 km^2, Table 1). According to the current geological and geochemical data set some granites (AG-types) seem to be more concentrated in the northern side of the batholith (Fig. 1), but this needs to be studied in more detail in future works.

At the present level of exposure, the Hercynian SCS intrusive rocks are predominantly granitoids with rare gabbroids and intermediate rock types which cover less than 10 km^2 (Bea 1985; Villaseca *et al.* 1998a). Scarce geochronological data on these rare basic-intermediate massifs (Gredos massif. 340 Ma,

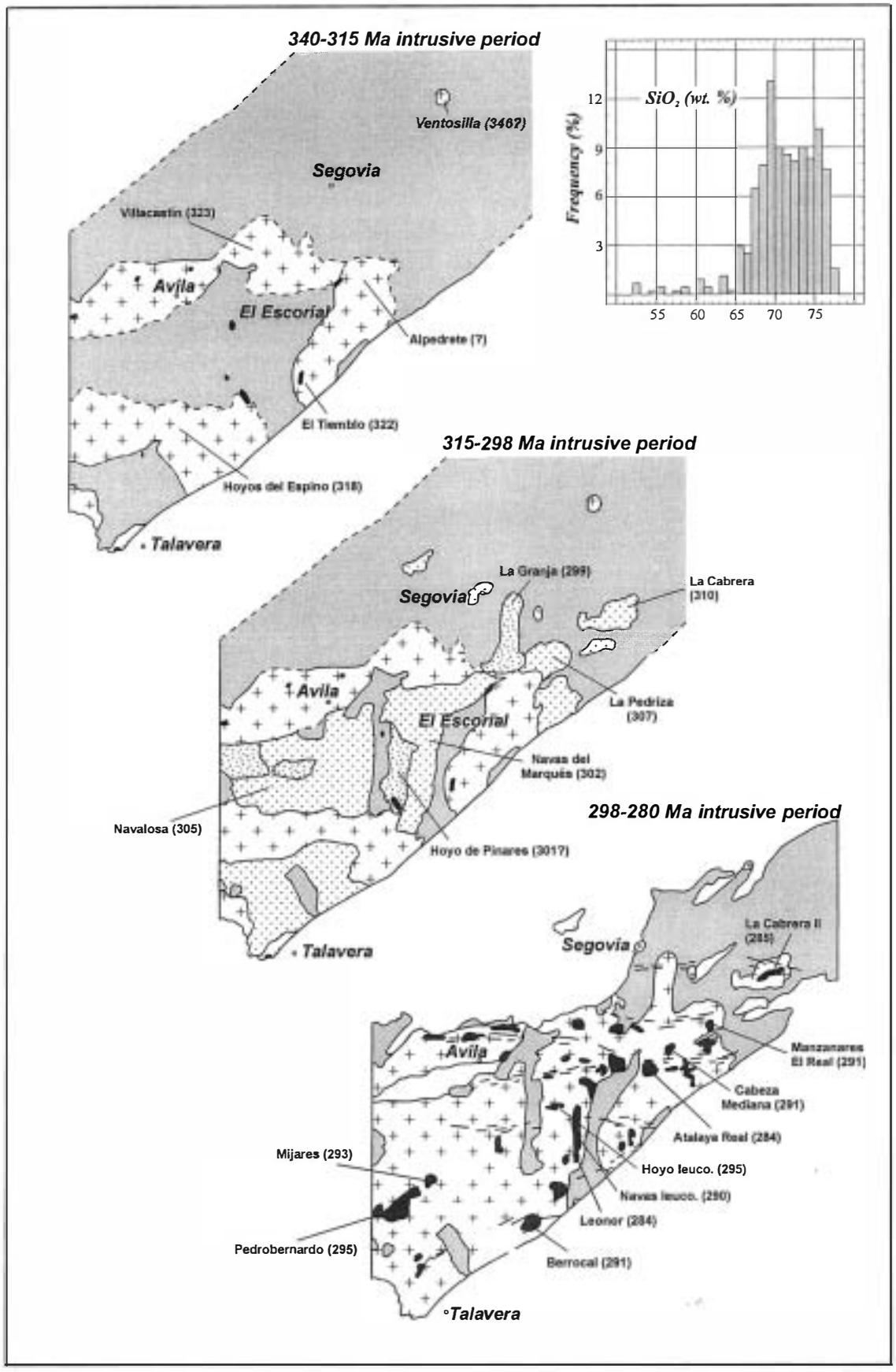

Figure 2 Temporal sequence of intrusive units in the SCS during the Hercynian orogeny; geochronological data are mostly based in Rb-Sr whole-rock isochrons (see references in Table 1); inset shows a histogram of SiO_2 content of the SCS granitoids (n = 450).

Table 1 General features and averaged geochemical values of SCS monzogranitic plutons

Sector	Granite-type	Pluton	Surface (km^2)	Age (Ma)	Na_2O/K_2O	K/Rb	Sr (ppm)	Eu/Eu*	$(La/Yb)_n$	$(^{87}Sr/^{86}Sr)_t$	εNd_t	$\delta^{18}O$
Eastern SCS (Guadarrama)	AG (PI)	Ventosilla	2	346?	1·30 ± 0·3	226 ± 34	320 ± 40	0·87 ± 0·2	9·2 ± 0·4	0·70869	−5·4 −5·8	
Eastern SCS (Guadarrama)	AG (PI)	Villacastín	> 150	323	0·80 ± 0·2	181 ± 28	150 ± 15	0·50 ± 0·1	9·25 ± 1·75	0·7073	−5·53	9·3
Eastern SCS (Toledo)	CG (PS)	Mora-Ventas	515	320	0·78 ± 0·06	155 ± 15	120 ± 30	0·52 ± 0·07	6·8 ± 0·5	0·7103	−6·37	
Eastern SCS (Guadarrama)	BG (Trans.)	Sierra del Francés	28	315	0·81 ± 0·04	170 ± 20	95 ± 10	0·70–0·73	8·5 ± 0·9	0·7088	−7·7	
Eastern SCS (Guadarrama)	AG (PI)	La Cabrera	160	310	0·85 ± 0·08	219 ± 13	170 ± 29	0·45 ± 0·05	10·7 ± 1·65	0·7094	−6·53	
Eastern SCS (Guadarrama)	CG (PS)	Hoyo de Pinares	> 130	301	0·73 ± 0·07	175 ± 25	100 ± 15	0·59 ± 0·09	8·7 ± 0·4	0·7100	−5·22	
Eastern SCS (Guadarra,a)	AG (PI)	Navas Marqués	300	302	0·77 ± 0·07	179 ± 22	89 ± 24	0·50 ± 0·14	8·3 ± 4·3	0·7097	−5·1 −5·5	
Eastern SCS (Guadarrama)	CG (PS)	Alpedrete	350	300?	0·85 ± 0·05	180 ± 25	160 ± 30	0·50 ± 0·05	9·9 ± 1·2	0·70896	−6·31	9·4–9·5
Eastern SCS (Guadarrama)	AG (PI)	La Granja	85	299	0·79 ± 0·12	186 ± 17	130 ± 30	0·44 ± 0·08	9·1 ± 1·25	0·71212	−6·49	
Eastern SCS (Guadarrama)	CG (PS)	Cabeza Mediana*	7	291	0·89	172	95	0·45	7·9	0·71127	−6·64	9·5
Eastern SCS (Guadarrama)	AG (PI)	Atalaya Real	18	284	0·75 ± 0·03	197 ± 4	149 ± 18	0·50 ± 0·1	11·7 ± 3·25	0·7128	−6·00	8·9–9·1
Central SCS (Gredos)	AG (PI)	Cardeñosa-Avila	> 150	321?	0·91 ± 0·03		170 ± 26	0·66 ± 0·1	8·50 ± 2·72			8·9 ± 0·6
Central SCS (Gredos)	CG (PS)	Hoyos del Espino	> 300	318	0·62 ± 0·05	180 ± 15	145 ± 20			0·7084	−6·1 −6·3	
Central SCS (Gredos)	BG (Trans.)	Navalosa	820	305	0·81 ± 0·03	187 ± 25	150 ± 25	0·52–0·67	11·35 ± 3·5	0·7083	−4·0 −7·1	9·8
Central SCS (Gredos)	CG (PS)	Pedrobernardo*	45	295	0·60 ± 0·02	151 ± 5	95 ± 6	0·30 ± 0·1	23·1 ± 2·5	0·7123		
Western SCS (Béjar)	BG (Trans.)	Béjar BG	> 150	316?	0·81 ± 0·03	188 ± 15	151 ± 29	0·53 ± 0·1	9·95 ± 3·69	0·70838–0·70910	−3·9 −8·0	9·0 ± 0·4
Western SCS (Béjar)	CG (PS)	Béjar CMG	120?	307?	0·77 ± 0·03	153 ± 30	159 ± 30	0·50 ± 0·1	11·68 ± 3·37	0·70799–0·70897	−4·7 −7·8	9·6 ± 0·3

Granite-types are explained in section 2 of the text. AG-type = biotite granite locally with accessory amphibole; BG-type = biotite granite *ss*; CG-type = biotite granite with accessory cordierite. Geochemical data from Guadarrama sector are from Casillas (1989), Casillas *et al.* (1991), Pérez-Soba (1991) and Villaseca *et al.* (1998a). Data from Gredos sector are based on Bea (1985), Ugidos & Recio (1993), Bea *et al.* (1994), Moreno-Ventas *et al.* (1995) and Herreros (1998). Data from Béjar sector are based on Recio *et al.* (1992), Ugidos & Recio (1993) and Pinarelli & Rottura (1995). Oxygen data not included in Table 2 are from Recio *et al.* (1992).
* Data from Cabeza Mediana and Pedrobernardo leucogranitic plutons are averaged from their less evolved biotite-granites, supposed to be their parental magmas (i.e. lower granites of Pedrobernardo, Bea *et al.* 1994).

Bea *et al.* 1999; El Tiemblo massif. 322 Ma, Casillas *et al.* 1991) corroborate their geological interpretation as being either previous or related to the first pulse of the granite plutonism in this area. Moreover, basic magmas are also coeval to granite porphyry dyke intrusive events. So, minor basic intrusions were emplaced during most of the Hercynian magmatism.

The major intrusive units are composed of monzogranites (around 75% of the SCS granitoids) that locally grade to granodiorites (around 9% of granitoids), forming the so-called *regional granites*. The leucogranites (the other 16% of SCS granitoids) usually intrude as small units in the other granitoids, and they are commonly interpreted as highly fractionated magmas derived from the monzogranitic parental magmas (Bellido 1979; Casillas 1989; Villaseca *et al.* 1998a). The SCS batholith is monzogranitic on average.

2. SCS granite-types

The SCS batholith is almost entirely composed of peraluminous granitoids (Fig. 3). Three different granite-types have been distinguished. Petrographically they are biotite granites (as this mica is the main mafic phase in all the SCS monzogranites), but slightly modal differences between them could be found. The first type is composed of cordierite-bearing granites, which are moderately peraluminous granitoids in the sense of Villaseca *et al.* (1998c), and they have also received other names such as PS (for their affinity to some S-type granites, e.g. Dalgety suite of Chappell *et al.* 1991) (Villaseca *et al.* 1998a) or CG/CMG-types in the western sector of the SCS (Recio *et al.* 1992; Pinarelli & Rottura 1995). The second type is composed of metaluminous to weakly peraluminous granitoids, with locally accessory amounts of amphibole and allanite as index minerals, also called PI or AG-types by different authors (Villaseca *et al.* 1998a; Recio *et al.* 1992). A third transitional type, composed of biotite granitoids (*sensu stricto*) of intermediate peraluminous character, without peraluminous characteristic minerals, could be distinguished (BG-types of Recio *et al.* 1992; Pinarelli & Rottura 1995). For simplicity, in this work we use the descriptive terms CG-types (cordierite-bearing granites), BG-types (biotite granites) and AG-types (amphibole-bearing granites).

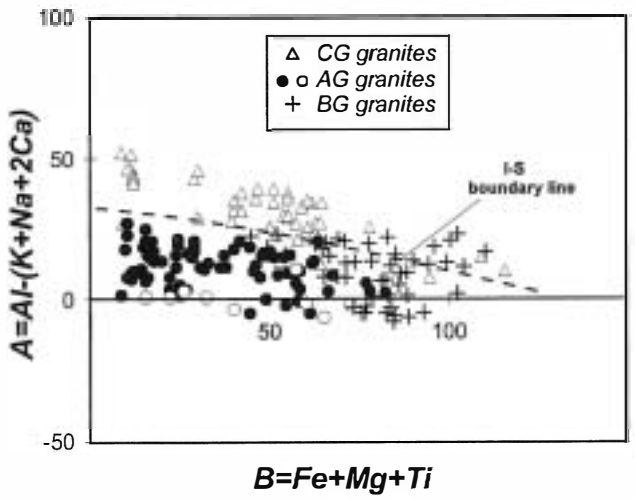

Figure 3 A–B parameters (see Debon & Le Fort 1983) for selected SCS granite-types; BG granites from Navalosa pluton (Herreros 1998) plot in intermediate fields between AG and CG-types; the less peraluminous suite of AG granites correspond to those of Atalaya Real pluton (open circles); I–S boundary line taken from Villaseca *et al.* (1998c).

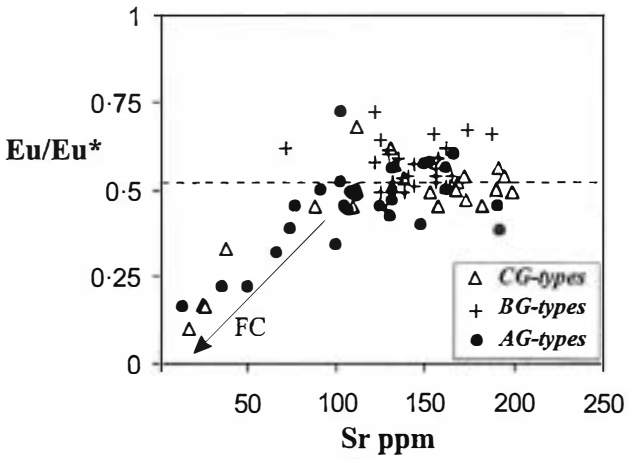

Figure 4 Variation of the Eu anomaly (Eu/Eu*) with Sr content for SCS granite-types; lower Sr contents and larger Eu anomalies correspond to more leucogranitic samples, a common feldspar fractionation trend shown by SCS granite-types (FC trend); Eu anomaly in parental monzogranites is mostly in the range 0·45–0·65, at *c.* 150 ± 50 ppm Sr, suggesting the presence of residual feldspars in the granulitic source (see text for further explanation).

SCS granites are mostly in the range 67·5–76·5 wt.% silica content and monzogranitic in composition, with around 70 ± 2 wt.% as the most frequent value (inset in Fig. 2). The majority of the SCS granites are peraluminous but some AG plutons are clearly subaluminous (e.g. Atalaya Real pluton, Fig. 3). Subtle higher Ca, Na, REE, Th, Y and Zr contents and lower P, Al and Nb contents in AG-types with respect to more peraluminous granites have been described (Casillas 1989; Villaseca *et al.* 1998a). At *c.* 73–75% SiO_2 content, SCS granites describe an inflection in geochemical trends in most of their plots. This has been interpreted and modelled as the result of the evolution of these suites by fractional crystallisation (Casillas 1989; Villaseca *et al.* 1998a). Feldspar fractionation is a common process during the evolution of SCS magmas, as shown by the decreasing Sr contents and increasing Eu anomaly in the more evolved rocks (Fig. 4). A compositional variation from granodiorite to leucogranite is recognised in plutons of the three described typologies, suggesting similar evolutionary patterns, but transitions from one granite-type to another in the same pluton have not been described. In fact, more complex fractionation trends with divergent evolution lines between AG and CG-types have been described elsewhere (e.g. Villaseca *et al.* 1998a), as illustrated in other peraluminous granitic suites (Chappell 1999).

3. Geochemical patterns with time: homogeneous vs heterogeneous batholiths

When comparing granitoids on a regional basis, it is important to eliminate the effects of magmatic differentiation. In order to compare similar lithologies, we have only used rock compositions bracketed by SiO_2 values of 67·5–72 wt.%, representative of the dominant monzogranitic regional facies of the different plutonic complexes of the area, also described as granite parents of the whole pluton (e.g. Casillas 1989; Bea *et al.* 1994). When comparing the averaged geochemical values summarised in Table 1, the SCS granites show a small range of variation in some major and trace element ratios, and also in isotopic ratios (Fig. 5). However, some small plutons plot outside the general trend (Fig. 5). So, data from one of the most felsic plutons of the sector (Pedrobernardo pluton, Bea

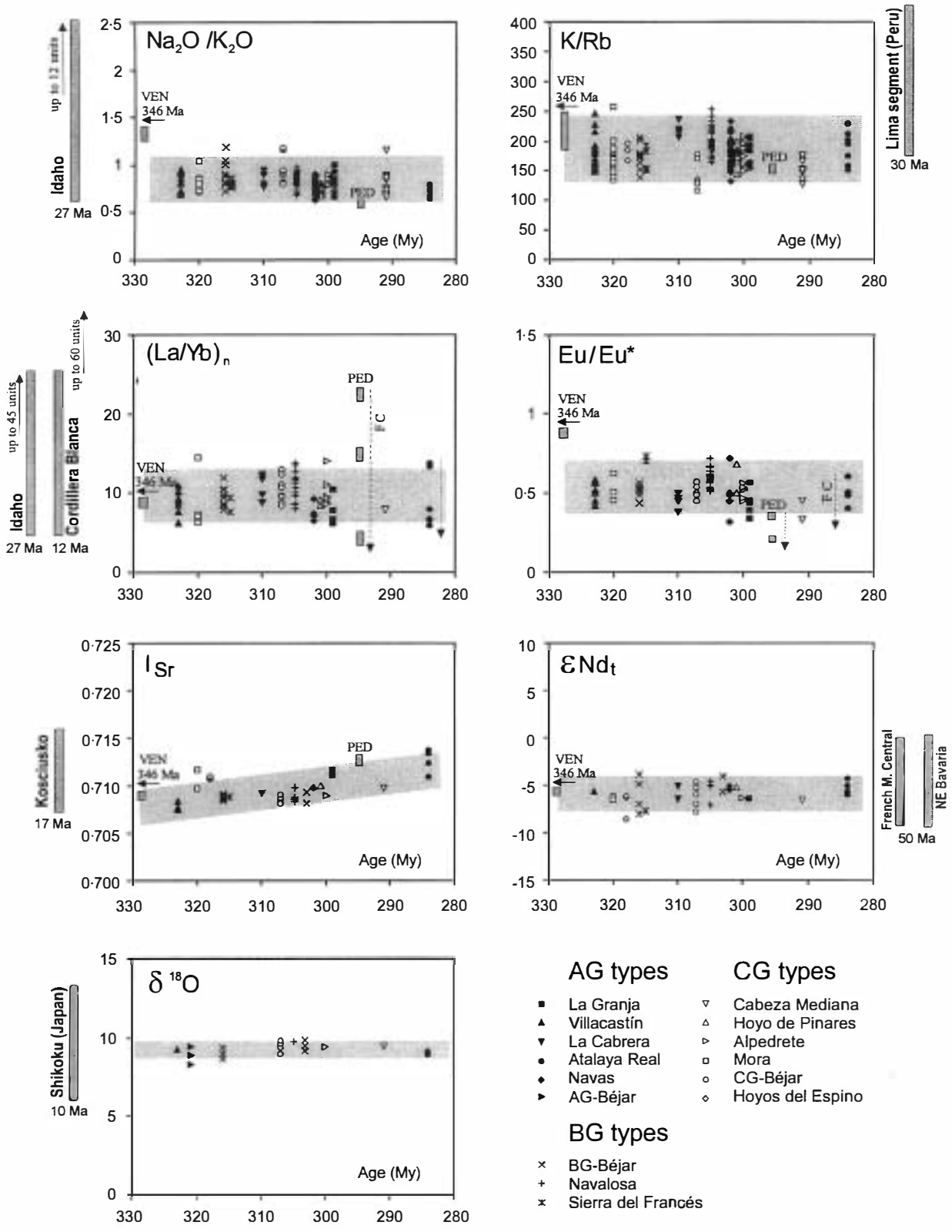

Figure 5 A summary of compositional parameters for the SCS batholith, illustrating the relative homogeneity in magma composition with time; data for the tonalitic Ventosilla pluton (VEN) (346 Ma in age) and the felsic Pedrobernardo pluton (PED) (295 Ma) are also shown, plotting outside the general range in some of the diagrams; the effect of feldspar fractionation in a plutonic suite is also shown in some of the plots (FC trend); with the exception of certain plutons, most of the SCS batholith shares some common geochemical features in comparison to other more complexly constructed batholiths (see also text); geochronological and chemical features for SCS granites are from Table 1; chemical bars and approximated time span of construction from other batholiths are: Idaho (Norman *et al.* 1992), Lima segment (Atherton *et al.* 1979), Cordillera Blanca (Petford & Atherton 1996), French Massif Central (Pin & Duthou 1990), NE Bavaria (Siebel *et al.* 1995), Kosciusko (Chappell *et al.* 1991) and Shikoku Island, SW Japan (Ishihara & Matsuhisa 1999).

et al. 1994, see Table 1) display a distinctive granite parent with a low Na_2O/K_2O ratio and more fractionated REE pattern (Fig. 5). These geochemical features combined with a high initial $^{87}Sr/^{86}Sr$ ratio were interpreted by Bea *et al.* (1994) as granites derived from metasedimentary sources. Also, the tonalitic-granodioritic samples of the Ventosilla pluton show a greater range of values in Na_2O/K_2O and Sr contents, and REE patterns with much lesser negative Eu anomalies than other SCS granites. Again, this suggests certain differences in the source-region characteristics. Nevertheless, other geochemical features of the Ventosilla pluton (including initial Sr and Nd isotopic ratios) are in the range of the SCS granites (Fig. 5).

SCS monzogranitic types show a restricted range of initial εNd from −4 to −8 (but most values are between −5·4 to −6·6, Table 1), and also exhibit a limited range in initial $^{87}Sr/^{86}Sr$, averaged from 0·7073 to 0·7129 (Pérez Soba 1991; Casillas et al. 1991. Moreno-Ventas *et al.* 1995; Pinarelli & Rottura 1995; Villaseca *et al.* 1998a; Herreros 1998). Only local hybridised facies richer in conspicuous mafic microgranular enclaves, show a more primitive and varied Sr, Nd isotopic composition (Moreno-Ventas *et al.* 1995; Villaseca *et al.* 1998a). Initial Sr isotopic ratios slightly increase with time but the trend follows an evolutive pattern for Rb/Sr ratios in the range 1–5, which are typical crustal values. A higher variability in the fractionation of the Rb/Sr ratio during crustal anatexis and also a higher modification of Sr values with time in comparison to Nd isotopic compositions, could be involved in the origin of the higher Sr isotopic heterogeneity shown by the SCS granites.

Preliminary $\delta^{18}O$, and Pb (for feldspars) isotopic data also reinforce the similarities among the analysed SCS granitoids. Five plutons from the eastern SCS (around La Pedriza pluton in the Guadarrama sector, Fig. 2) present Pb isotopic ratios within a narrow range: $^{206}Pb/^{204}Pb$ = 18·33, $^{207}Pb/^{204}Pb$ = 15·59–15·62, $^{208}Pb/^{204}Pb$ = 38·15–38·28 (Pérez Soba 1991). These tightly clustered values plot in the middle of the Pb isotopic linear array shown by western European Hercynian granites (Downes *et al.* 1997) in a field which is suggestive of involvement of lower crustal sources. Similarly, the three granite types in the western area give almost identical whole-rock $\delta^{18}O$ values, in the range 8·9–9·6‰ (Recio *et al.* 1992). For these reasons the SCS granites have been interpreted as being derived from distinct magma batches from a restricted range of parent sources (Villaseca *et al.* 1998a).

4. Magma sources

The Hercynian plutons do not have their sources in the neighbouring wall rocks. The intrusive granitoids show similar geochemistry over the entire region irrespective of the adjacent wall rock composition and metamorphic grade. Moreover, isotopic compositions of metamorphic wall rocks (Fig. 6) are clearly different than those of the granites (Recio *et al.* 1992; Villaseca *et al.* 1998a). Much of the actual debate on SCS granite petrogenesis is explained in terms of a mixed mantle–crustal source (Recio *et al.* 1992; Moreno-Ventas *et al.* 1995; Pinarelli & Rottura, 1995; Castro *et al.* 1999) or a mainly lower crustal origin (Villaseca *et al.* 1998a; Bea *et al.* 1999; Villaseca *et al.* 1999).

For this study we have performed new oxygen isotopic analyses of granites from the central and eastern areas of the SCS batholith and also of potential protoliths (Table 2).

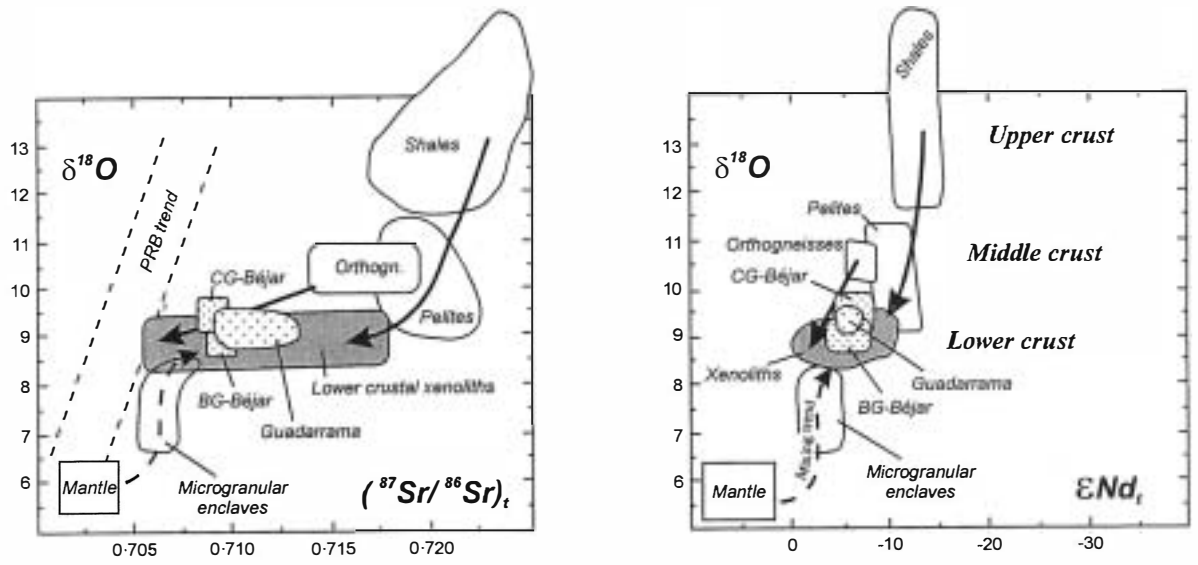

Figure 6 Plots of initial ($^{87}Sr/^{86}Sr$) and ε_{Nd} values vs $\delta^{18}O$ values for SCS granites and surrounding Hercynian rocks: initial values for metamorphic rocks are calculated assuming an averaged Hercynian age of 300 Ma; granitic rocks plot mostly within the lower crustal xenoliths field, suggesting their deep crustal provenance; metamorphic rocks show a marked lowering in their isotopic ratios with depth, as has also been proposed for other crustal sections (see also Villaseca *et al.* 1999, and references therein); this isotopic shift of crustal lithotypes has to be considered when comparing granites with their surrounding metamorphic rocks; microgranular enclaves in SCS granites plot in an intermediate field between granites and mantle-derived magmas, suggesting chemical interactions between the two; see text for further explanations; mantle composition and the Peninsular Ranges Batholith (PRB) trend are also shown for comparison (Taylor 1988); data of Béjar granites are from Recio *et al.* (1992) (oxygen isotopes) and Pinarelli & Rottura (1995) (Sr, Nd isotopes); data of epizonal precambrian shales of the Central Iberian Zone are from Ugidos *et al.* (1997); microgranular enclaves isotopic range is extrapolated from Recio *et al.* (1992), Pinarelli & Rottura (1995) and Moreno-Ventas *et al.* (1995); Sr–Nd isotopic data of lower crustal xenoliths (shaded field) are from Villaseca *et al.* (1999); Sr–Nd data of SCS granites and wall-rocks (orthogneisses and pelites) are from Villaseca *et al.* (1998a); other oxygen data are from Table 2.

Table 2 Oxygen isotope values (in per mil) on whole-rocks samples of the SCS batholith and related metamorphic rocks.

Sample	Description	$\delta^{18}O$
SCS granitoids		
92460	*AG-type*. Granodiorite. Villacastín pluton	9·3
HV 555-355	*BG-type*. Monzogranite. Navalosa pluton	9·8
95916	*CG-type*. Monzogranite. Alpedrete pluton	9·4–9·5
76873	*CG-type*. Monzogranite. Cabeza Mediana pluton	9·5
95922	*AG-type*. Granodiorite. Atalaya Real pluton	8·9–9·1
Wall-rocks		
62978	Augen orthogneiss	10·9
100942	Augen orthogneiss	10·1–10·4
77758	Metapelite	9·1–9·3
93202	Pelitic migmatite	11·0
93201	Pelitic migmatite	11·4
Granulitic xenoliths		
81846	Felsic metaigneous	8·9–9·3
95148	Felsic metaigneous	8·7–8·9
U-50	Felsic metaigneous	8·3
U-93	Felsic metaigneous	8·9
77750	Metapelite	9·1–9·6

Oxygen isotopic ratios were measured by C. Recio in the Servicio General de Análisis de Isótopos Estables de la Universidad de Salamanca following the method described in Recio *et al.* (1992).

In Figure 6 it is possible to observe that lower crustal xenoliths perfectly match (in terms of Sr, Nd and oxygen isotopic ratios) the compositional range of SCS granites. The felsic (mostly metaigneous in origin) granulite xenoliths have initial Sr isotope ratios in the range 0·706–0·713 εNd values from −2·6 to −8·2 (Villaseca *et al.* 1999) and $\delta^{18}O$ values of 8·7–9·3‰ (Table 2). In view of the residual character of these granulites, from which granitic melts similar in composition to those of outcropping granites have been extracted (Villaseca *et al.* 1999), a mainly lower crustal origin for most of the batholith could be deduced. Moreover, the new oxygen isotope data presented in this work reinforce the geochemical similarity between the defined SCS granitic series and their lower crustal sources (residual granulites).

In Figure 6 the Sr, Nd and oxygen isotopic compositional range of mafic microgranular enclaves (MME) from the Béjar granites (Recio *et al.* 1992; Pinarelli & Rottura 1995) and Gredos granites (Moreno-Ventas *et al.* 1995) are plotted, and they are compared with those of the SCS granitoids and with the composition of mantle-derived rocks (M) (Taylor 1988). The distribution of the MME defines a trend broadly connecting the field of mantle-derived rocks to SCS granites, suggesting that mixing of basic magmas and crustal melts may account for this kind of enclave and for the local MME-rich facies of some granitic plutons (e.g. Moreno-Ventas *et al.* 1995). Nevertheless there is no isotopic indication for significant mantle contribution to the SCS geochemistry. As in other peraluminous Hercynian batholiths, the geochemistry of SCS granitoids reflects the composition of its crustal sources, the minor mafic component being of very limited importance (e.g. Di Vincenzo *et al.* 1996; Gerdes *et al.* 1998).

In a similar way, assimilation models to explain the origin of the most peraluminous SCS granites (i.e. CG types, Ugidos & Recio 1993) are severely restricted, as shown by the contrast in isotopic composition between granites and related wall rocks (middle/upper crustal levels) and the lack of any mixing trend between them (Fig. 6). The (Sr, Nd, O) isotopic data of the SCS granites do not require a shallower crustal component.

5. Magma generation

Apart from the material source for any magmatic event, it is also important to discuss the source of heat energy for melting. Melt normally is not present within the lithosphere and must be produced by heating, lowering pressure, adding volatiles, or a combination of these mechanisms brought about by some tectonic event (Speer *et al.* 1994). In the case of the SCS granites, their relation to the thermal evolution of the Hercynian collision seems to be conclusive but, nevertheless, other hypotheses have arisen.

Heating by mafic magma underplating and consequent evolution through crustal interaction have been suggested to explain the origin of SCS granites (Pinarelli & Rottura 1995; Moreno-Ventas *et al.* 1995; Castro *et al.* 1999). Theoretical models involving an important contribution of mantle-derived magmas in the genesis of the SCS batholith require a large volume of basic rocks, which is not present in the area. A minor involvement of coeval mafic magmas with the granitoids is enough to explain the presence of local intermingling and mafic microgranular enclaves in granitoids, as previously discussed. There is no evidence of basic material either eroded (sedimentary-related rocks) or hidden in deeper crustal levels. The xenolith suite of granulitic rocks from the lower crust is conclusive in this respect: 95% felsic metaigneous rocks, 5% pelites and rare charnockitic xenoliths (Villaseca *et al.* 1999). Geophysical data also support such a felsic lower crust beneath the SCS (Banda *et al.* 1981).

Large volumes of basic magmas are required to produce large granitic batholiths and, furthermore, basalt-induced crustal melting is rapid (10^2–10^3 y, Huppert & Sparks 1988). Thus large-scale and continuous basic magmatism would need to persist for more than 40 Ma to explain the described Hercynian magmatic event.

The SCS metamorphic belt in the eastern areas (Sierra de Guadarrama) shows an increase in metamorphic grade towards the central block where the batholith crops out. The exposed metamorphic series locally attained 750–800 °C at 4–6 kbar (1 kbar = 100 MPa) during the Hercynian metamorphic peak (mid-crustal granulitic terranes) but P–T estimates on granulitic xenoliths record metamorphic conditions of around 900 °C and 8–10 kbar for the lower Hercynian crust (Villaseca *et al* 1999). These P–T estimates are in accordance with a regional geothermal gradient of 30–40 °C km^{-1}, which is slightly higher than those obtained in typical thermal models of crustal thickening during continental collision (Patiño Douce *et al.* 1990; Gardien *et al.* 1995). This could result from a combination of two factors (Villaseca *et al.* 1998a): (a) the marked felsic composition of the SCS crust which contains a high concentration of heat-producing radioactive elements, and (b) the considerable crustal thickening attained during collision, estimated to be around 70–80 km, more than doubling the original thickness (Villaseca & Barbero 1994). Temperatures in excess of 900 °C at the Moho permit significant partial melting of the felsic crustal materials: between 40–60% and liquid for pelitic rocks, and 5% to 35% liquid for quartzofeldspathic rocks (Gardien *et al.* 1995).

P–T estimates for crystallisation of high-temperature minerals in SCS granitoids (probably close to their liquidus conditions, in some cases defining residual paragenesis, e.g. Casillas 1989; Eugercios 1994) are in agreement with thermal conditions during the Hercynian orogeny (Fig. 7). Magmatic epidote and muscovite are absent in granodiorites and monzogranites, only rare garnet (of grossular-almandine composition) or Al-rich hornblende indicates that SCS intrusives mostly crystallised at pressures lower than 6–8 kbar (Fig. 7). These P–T estimates plot close to the estimates made on restitic granulites

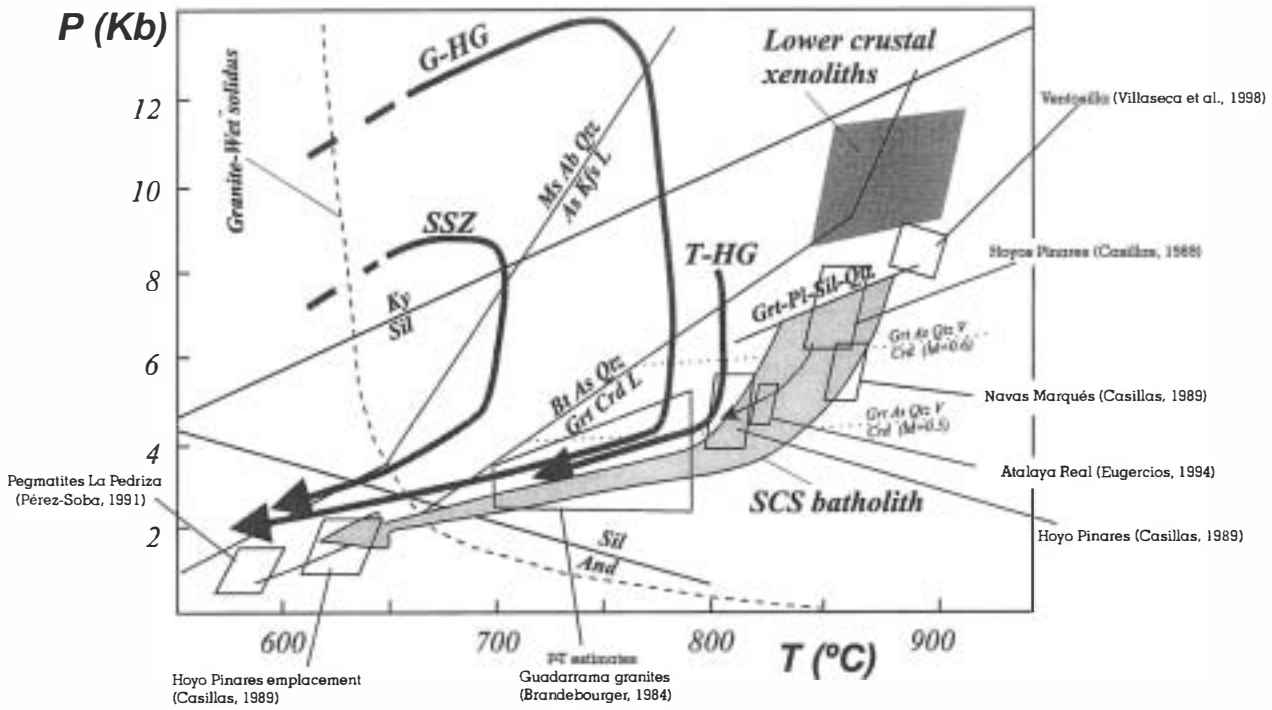

Figure 7 P–T diagram showing the estimated conditions during the generation and emplacement of the SCS granites; Grt–Pl–Sil–Qtz equilibrium is from Casillas (1989) for Hoyo de Pinares and related plutons; high P–T estimates in granites (Casillas 1989; Eugercios 1994; Villaseca *et al.* 1998b), are mainly based on Grt–Bt, Grt–Crd, Ti- and Al-in-hornblende geothermobarometry, and are used to define the general P–T conditions of generation of the SCS batholith; emplacement conditions of the SCS batholith over a range of 4–2 kbar reflect exhumation during batholith emplacement, although a clear correlation between emplacement pressure and age has not been yet established; SSZ represents the P–T path of the sillimanite zone of Somosierra sector (E of SCS) (Escuder Viruete *et al.* 1998); G–HG represents the P–T path of high-grade areas of the Guadarrama sector from Villaseca & Barbero (1994); T–HG represents the P–T path of the high-grade anatectic complex of Toledo (Barbero 1995); lower crustal estimates are from Villaseca *et al.* (1999); the mineralogical and chemical nature of SCS granites is consistent with a generation by crustal anatexis of peraluminous sources in the lower crust (see text); curve of granite-wet solidus from Johannes (1984); other curves and mineral symbols are from Spear *et al.* (1999).

from the SCS lower crust (Villaseca *et al.* 1999) suggesting the possibility of an attainment of equilibrium between them (Fig. 7). This is an additional support for the generation of these granitic magmas by crustal anatexis of felsic peraluminous rocks in the deeper crust. Hercynian granitoids could mainly represent recycling of older continental crust with no substantially new additions.

6. Discussion

The lack of significant compositional differences between the three granitic suites, maintained during a long period, suggests a similarity in nature of their source regions and conditions of magma generation. The similarity of REE patterns among monzogranitic rocks ranging in age from 325–280 Ma (Fig. 5) suggests that accumulation or removal of early crystallising phases did not greatly disturb the REE abundances. Therefore, the REE pattern must reflect the mineralogy of the source residue. Similarly, the narrow range of trace element ratios such as Rb/Zr, Y/Nb or REE/Th among SCS monzogranites might be an indication of the sources involved. This suggests that all source residues contained feldspars (plagioclase and/or K-feldspar) in order to explain both the low Sr contents and the marked negative Eu anomaly in all parental granite types. This is in good agreement with the residual assemblages in granulitic xenoliths of the SCS lower crust (Villaseca *et al.* 1999).

The limited range of isotopic ratios shown by SCS granites suggests the involvement of very abundant and fertile lithotypes. Two protoliths have these characteristics in the central segment of the Iberian Hercynian Belt. Metapelites have been described as protoliths involved in the genesis of certain anatectic granites during metamorphic peak (Barbero & Villaseca 1992). Orthogneisses are also very common in the exposed metamorphic series and chemically they have closer ratios (at least in initial Nd signatures, Villaseca *et al.* 1998a) to the SCS granites. As also shown by Villaseca *et al.* (1999), felsic metaigneous protoliths are the most common lithology in lower crustal levels, as *c.* 95% of the granulitic xenolith suite is of this nature.

Although fertile crustal lithotypes are abundant in the SCS (quartzofeldspathic metaigneous rocks as better candidates for granite sources) it is paradoxical that in the chemistry of the granites there would not appear any reflection of evolution of melting conditions (depth of melting, residual phases, melt fraction, . . . etc.) with time. Would the constancy in LREE/HREE ratios in SCS granites with time, reflect a constancy in protoliths and depth of partial melting? In continental margins the geochemical asymmetry of some batholiths in part reflects either the progressive involvement of thicker parts of the continental margin wedge or the depth of melting (Gromet & Silver 1987). Similarly, in granitic plutonic complexes of more intracontinental settings, an evolution of melting depth with time has also been described (e.g. the Idaho Batholith, Norman *et al.* 1992). Moreover, in thermal orogenic models there is an evolution of melting levels with time (Patiño Douce *et al.* 1990; Thompson & Connolly 1995). So, why is there not any important image in SCS granite chemistry of these changeable melting conditions? One factor explaining this would be the

broad garnet stability field in quartzofeldspathic rocks. Garnet is the main mineral controlling HREE in granulite melting conditions for pelitic and felsic protoliths (Ayres & Harris 1997). The garnet stability field is very broad for these lithotypes, ranging from middle to lower crustal levels (4–15 kbar, Spear *et al.* 1999). In other words, garnet is always present in the residual assemblage during partial melting in this Hercynian sector.

REE, Y, P, Zr and Th are also controlled by the presence of apatite, zircon, monazite or xenotime in the melting event (Watson 1985; Watt & Harley 1993; Ayres & Harris 1997). SCS granites seem to have resulted from disequilibrium melting of crustal protoliths, as their low total REE concentrations are much less than expected in dissolution models. Monazite is the main reservoir of REE in peraluminous rocks (where allanite is absent) (e.g. Nabelek & Glascock 1995; Ayres & Harris 1997). When considering REE modelling based on monazite solubility in partial melting processes (Montel 1993), no reasonable combination of T, D or H_2O solubility can reproduce the low REE concentrations in the SCS granites (Fig. 8). REE concentration in the melts is mostly conditioned by temperature, and to a lesser extent by melt composition (D factor) and water content (see Montel 1993). Using reasonable values for these parameters, the SCS granites had to show REE concentrations close to an average value of 620 ppm, intermediate value between 240 ppm (for the more peraluminous granites with D values *c.* 1·00 and low water contents of only 2 wt.%, at low temperature of melting: 850 °C) and 975 ppm (for less peraluminous granites with D values *c.* 1·25, undersaturated higher water contents of 5 wt.%, at 900°C). This indicates lack of saturation of granitic melts by monazite dissolution during melting. The same undersaturation is deduced for Zr using zircon dissolution modelling. Using this modelling for hydrous peraluminous granitic melts (Watson & Harrison 1983), saturation must be around 500 (±200) ppm in the melt, which is far from the lower concentration range shown by the SCS granites (Fig. 8).

This trace-element undersaturation has been interpreted as a consequence of two main factors: (a) heterogeneous distribution of accessory phases in the source and morphological features that inhibit quick crystal dissolution, e.g. large crystals totally included in major phases, isolated from a partial melt and having few chances to be totally dissolved (Watt & Harley 1993; Nabelek & Glascock 1995); (b) melt segregation rates exceeding accessory phases dissolution rates (Sawyer 1991). Nevertheless, a significant amount of some trace elements resides in major phases (garnet, plagioclase, alkali feldspar) of granulitic restites. This would result in contrasting behaviour of these major phases during melting processes with respect to what occurs during crystallisation from felsic granitic melts (Reid 1990). In this respect, two factors point to compatible behaviour of some minor and trace elements in feldspars during melting under granulitic conditions: (i) SCS granulitic xenoliths are not depleted in REE, P or Zr contents (Villaseca *et al.* 1999), and (ii) feldspars are major carriers of LREE and P in granulites (Reid 1990; Bea 1996; Villaseca *et al.* 1999) (Fig. 9). A similar situation may be envisaged when residual garnet is involved. In this case, HREE and also Zr from xenotime and zircon dissolution may be transferred to the newly formed granulitic garnet (Bea & Montero 1999; Fraser *et al.* 1997). So, trace element components from dissolution of accessory phases during melting are not necessarily partitioned to the melt fraction, as a substantial part would be introduced in the newly formed incongruent minerals of melting reactions. In any case, initial trace element geochemical variability in granite melts is severely reduced by the lack of attainment of equilibrium conditions during melting, because compositions are buffered compared to those expected by dissolution models.

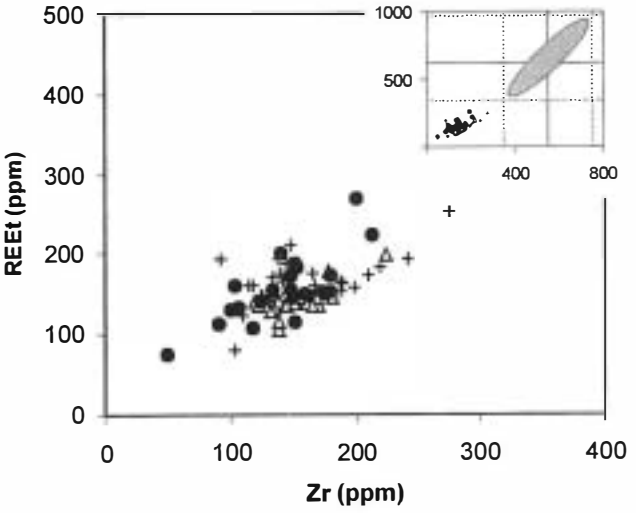

Figure 8 Plot showing total REE vs Zr contents in SCS granites (same symbols as in Fig. 3); inset shows estimated concentrations in granitic melts saturated with monazite and zircon (shaded field) at various temperatures (850–900 °C), water contents (2–5 wt.%) and melt compositions (D in the range 1–1·25 and M *c.* 1·3–1·6) using the models of Montel (1993) and Watson & Harrison (1983) (see text for further explanation); Zr and total REE contents in SCS granites are clearly lower than those predicted by solubility models.

Finally, when crustal melts derived from a range of sources do not subsequently have the opportunity to accumulate into large magma bodies (where efficient mixing could be enhanced) the granite massif will retain its chemical heterogeneity. This is well exemplified by felsic granitoids derived by low-melt fractions in short-lived magmatic systems such as the Himalayan and other leucogranites (Deniel *et al.* 1987; Krogstad & Walker 1996; Searle *et al* 1997). In the same way, granitic plutons showing evidence of rapid rates of extraction, ascent and emplacement of individual melt batches, would inhibit widespread mixing between melts (Pressley & Brown 1999). In central Spain, plutonic complexes have batholithic dimensions (Table 1), and lack sharp contacts between the monzogranitic internal units. SCS granitic plutons probably acquired definitive homogeneous geochemical features as a consequence of a complex combination of limited crustal sources in a geodynamic setting where melting conditions were maintained for a long time. This long-lived magmatic system, combined with ascent and emplacement rates where crystallisation of melt batches was slower than the rate of arrival of successive batches of melt, allowed the progressive growth of the plutonic complex and, consequently, enhanced the possibility of convection and physical mixing between similar melts from not very different sources. Thus the generation of voluminous and relatively chemically and isotopically homogeneous plutons is more likely. Nevertheless, the Atalaya Real massif shows increasing initial isotopic Nd ratios with increasing SiO_2 content, suggesting that mixing of magmas derived from heterogeneous sources was not complete (Villaseca *et al.* 1998d). New geochemical studies combined with different isotopic systems are needed for better evaluation of these proposals.

7. Conclusions

The SCS is a remarkably homogeneous batholith showing a restricted range of geochemical granite types without any evolutionary pattern related to time. During Hercynian times

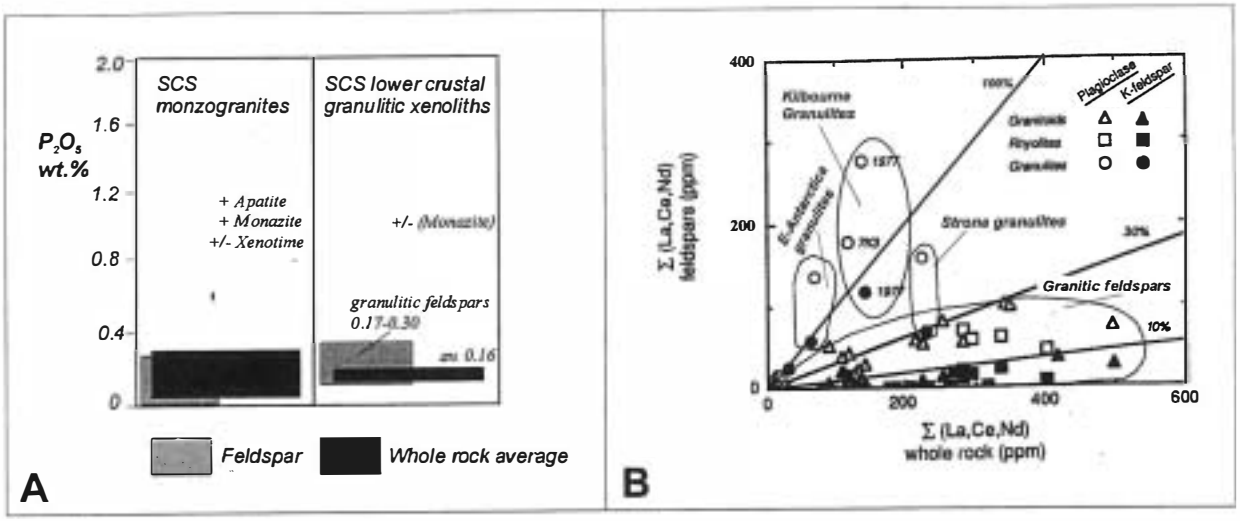

Figure 9 Comparison of P_2O_5 and LREE contents in feldspars and whole rocks from granitoids and granulites: (A) phosphorous contents in feldspars and whole rocks from SCS monzogranites (from our own data set) compared to data from lower crustal xenoliths (Villaseca *et al.* 1999); in these granulites phosphorous is mainly contained in feldspars in accordance with their generalised lack of phosphate phases. (B) LREE data from granitoids, rhyolites and granulites mainly based on the work of Reid (1990); other granulite data: Strona (Bea 1996) and E-Antarctica (Watt & Harley 1993); in lower crustal granulites most of the LREE are contained in residual feldspars attaining concentrations of 30–100% of the whole rock content; involvement of accessory phases in residual granulites is very low, again in accordance with their petrographic scarcity; as a consequence, dissolution of accessory phases during melting does not control trace element geochemistry of granitic melts when feldspars are abundant residual granulitic phases.

prealuminous granites with small variations in chemical composition, i.e. restricted range of ratios of Na_2O/K_2O (0·60–0·95), K/Rb (140–240), $(La/Yb)_n$ (6–13) and Eu/Eu* (0·34–0·62), intruded continuously in the SCS. This constancy in chemical characteristics of monzogranites is also reflected in their isotopic signatures: most have initial $^{87}Sr/^{86}Sr$ ratios in the range 0·7073–0·71229, initial εNd values varying between $-5{\cdot}4$ and $-6{\cdot}6$ and $\delta^{18}O$ values in the narrow range 8·9–9·6‰. In addition to this scenario, sporadic intrusions of granitic magma batches displaying different geochemical signatures, either with a stronger pelitic source derivation (e.g. Pedrobernardo pluton, Bea *et al.* 1994) or from intermediate-composition igneous sources (e.g. Ventosilla pluton, Villaseca *et al.* 1998b) are also observed.

This monotonous granitic batholith is in marked contrast with other Hercynian batholiths (French Massif Central, NE Bohemian Massif) or batholiths from intracontinental settings (e.g. Cordillera Blanca, Idaho, Colville) where either a variable mantle contribution (or more refractory components), or a variation in melting depth with time leads to more geochemically complex granitic batholiths. The SCS batholith clearly contrasts with the geochemically segmented and asymmetrically composed cordilleran batholiths of plate margins (e.g. Peruvian Coastal Batholith, Peninsular Ranges Batholith).

Some factors related to the Hercynian continental collision have contributed to the origin of this long-lived homogeneous magmatic system. The main factor is the involvement of a limited range of crustal sources in the origin of the batholith. Geochemical and isotopic features of SCS granitoids are compatible with felsic lower crustal sources. The essentially felsic nature of this crustal segment and the limited basic input during orogenesis leads to a restricted variety of granitic magma batches with a limited range of isotopic compositions.

When a limited range of sources are involved in the genesis of a batholith, melting conditions are also more constrained. Uniformity in residual mineral assemblages (feldspars and garnet are always present in the granulitic residua), combined with a lack of attainment of equilibrium conditions during accessory phase dissolution in the crustal melting process, is suggested. Granitic melts never reach saturation contents in those trace elements controlled by these phases (REE, Th, P, Y, Zr . . .), restricting their chemical variability. This was in part due to the important role played by some major phases during melting under granulitic conditions, because a large fraction of some trace elements (LREE, P . . .) is hosted in residual feldspars.

Anatectic magma batches derived from a limited variety of interlayered crustal sources tend to obscure (and homogenise) their original chemical differences by mixing in mid-crustal major magma chambers. It has been suggested that similar processes of efficient mixing of melts from more than one source occur in other productive long-lived magmatic systems (e.g. mid-ocean ridges: Hess 1989; Marsh 1996).

8. Acknowledgements

We are grateful to the organisers of this Fourth Hutton Symposium, and Professor B. Barbarin in particular, for giving us the opportunity to participate in this meeting. We acknowledge Drs Calvin Barnes, Bernard Barbarin and an anonymous reviewer for their constructive comments. Drs Edurne Martinez and specially Luis Barbero are thanked for their corrections and suggestions to a previous version of our paper. Drs Clemente Recio and Jose María Ugidos (Servicio General de Análisis de Isótopos Estables, Universidad de Salamanca) are thanked for their diligence in the performance of oxygen isotope analyses. This work is included in the objectives of and supported by the PB96-0661 DGES project of the Spanish MEC.

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MS received 21 September 1999. Accepted for publication 9 May 2000.